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Soviet research on controlled fusion

Like workers in other countries engaged in the quest for useful power from deuterium, Soviet physicists face the severe problem of stabilizing the hot "plasma" needed for fusion to occur. They have a vigorous programme for tackling the problem in a variety of ways

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ONE of the most fascinating scientific and technical problems of our age is the use of the reserves of excess energy concentrated in the nuclei of the lightest elements. This energy can be liberated in the processes of fusion of light nuclei when they collide with one another: the nuclei of hydrogen isotopes, deuterium and tritium, are of the greatest practical interest in this respect. To get an idea of the possible energy yield of such reactions, consider that if all the nuclei contained in a single gram of deuterium reacted with one another, the energy generated would equal about 20 million kilocalories.

Before describing the experiments we have been carrying out in the Soviet Union, it would be as well to recapitulate the problem which confronts all research workers in this field. Nuclear fusion can begin in a substance only if the atomic nuclei move at sufficiently high speeds to overcome their mutual electrostatic repulsion and come into close contact. The speed of the nuclei in the substance increases with the temperature; and only when the substance is at a very high temperature indeed can useful fusion reactions begin—which is why they are termed thermonuclear reactions.

The first traces of fusion reactions can be detected in laboratory conditions when deuterium (or a mixture of deuterium and tritium) is heated to a temperature of the order of 1,000,000°C. However, thermonuclear reactions can become a practical source of energy only at a temperature of several hundred million degrees. At these super-high temperatures the atoms lose their electron shells and the substance is transformed into a state of fully ionized plasma; that is to say it becomes a gaseous mixture of stripped atomic nuclei and free electrons.

Thus to carry out thermonuclear fusion we have to create a high-temperature deuterium or deuterium-tritium plasma. We are not concerned here with initiating a destructive thermonuclear explosion with the aid of an A-bomb detonator, but with making it possible for the reactions to follow a steady course under controlled conditions, so that the energy thus generated can be put to technical use. Accordingly it is necessary that the high-temperature plasma should exist for a sufficiently long period of time.

The main difficulty lies in the fact that the plasma tries to rid itself of the super-high temperature imposed upon it, mobilizing for this purpose various mechanisms of heat transfer. The most serious source of thermal losses is normal thermal conduction. Heat losses induced by the thermal conduction of the plasma increase faster than the cube of the temperature, and at a temperature of the order of 100,000°C are already so great that further heating is possible only if use is made of extremely effective methods of heat insulation which completely exclude contact between the hot plasma and the walls of the vessel in which it is enclosed. This means that the heated plasma must be suspended in a vacuum like Mohammed's legendary tomb, which, tradition tells us, hangs between Heaven and Earth.

Today the only conceivable method for such radical heat insulation is based on a scheme whereby the charged particles in the plasma are subjected to the influence of a strong magnetic field. They are unable to move across the field and so it becomes possible to contain the plasma in a "magnetic bottle" which holds it away from contact with the walls of the chamber. This is the principle of the magnetic heat insulation of plasma—a principle discovered by physicists working independently of one another in the USSR, Britain and the USA.

In the Soviet Union the idea of magnetic heat insulation was first put forward by Sakharov and Tamm. It provided the impetus for the development in the early 1950s of experimental methods of high-temperature plasma production. The most natural method of realizing this idea involves passing a powerful electric current through the plasma. The current carries out the two functions of setting up the magnetic field for heat insulation and of heating the plasma (by the Joule effect).

In the first experiments made in the USSR to study this method, powerful electrical discharges of short duration were used. A current of several hundred thousand amps was passed through a cylindrical discharge tube made from porcelain or quartz and filled with deuterium under low pressure (of the order of 0.1 mm Hg.). The gas was quickly ionized and a cylindrical plasma column formed in the discharge tube. The rings of the magnetic field which embraced this column of plasma behaved like resilient rubber cords. They pressed upon the plasma, tore it away from the side wall and compressed it into an incandescent filament running along the axis of the discharge tube (Figure 1).

By this process it was possible to bring the temperature of the compressed plasma filament up to several million degrees; and this was the first success in the initial phase of the Soviet research. However, the period of time for which the high temperature could be maintained was infinitesimally short—of the order of one microsecond. The current-compressed plasma filament is capable only of a very brief existence, since it is susceptible to a whole range of dangerous deformations which alter its shape and lead to serious interaction between the plasma and the tube wall. This instability arises because the electrodynamic forces tend to increase any deformation that occurs and the plasma, having no rigidity, does not resist the deformation.

In order significantly to increase the lifetime of the plasma in its high-temperature state we must have means of suppressing its instability. Theoretical analysis shows that the instability may be much reduced or even completely eradicated if a coil wound around the outside of the vacuum chamber is used to set up within the latter a powerful magnetic field directed parallel to the current travelling through the plasma. In this case it is not wise to heat the plasma in a straight discharge tube, since the electrodes at the two ends are the cause of heavy cooling of the plasma. Therefore in all the main studies of the heating of plasma by current in the presence of a stabilizing field, the plasma filament was created within a chamber having the shape of a hollow toroid. These "doughnut" chambers are usually made from stainless steel (wall thickness 0.2-0.3 mm). The current in the plasma is excited by induction.

Attention has been mostly devoted to two main ways of producing hot plasma in doughnut chambers.

In the first one, use is made of an external stabilizing field of comparatively low initial intensity (of the order of several hundred oersteds). It is supposed that the following process may thus be put into effect: The current passing through the plasma tends to compress itself and transform itself into a narrow filament. In compressing the plasma carries with it the lines of force of the longitudinal stabilizing field. According to theory, these lines are glued, as it were, to the substance (provided it possesses sufficient conductance), and they form a resilient framework which imparts a certain degree of rigidity to the plasma.

This method was first investigated in detail in England on the *Zeta* and *Sceptre* assemblies. In the Soviet Union an assembly has been constructed in Leningrad for similar researches. This is the *Alpha*, which differs little in its design from *Zeta*. Research on this assembly is being carried out jointly by the Research Institute of Electrophysical Apparatus and the Leningrad Physico-Technical Institute.

In the other the method for producing a stable plasma loop, the longitudinal field is many times greater than that created by the plasma current. Theory predicts that systems of this type should afford extremely effective suppression of the main forms of plasma instability.

For a number of years doughnut systems of this type with longitudinal fields of up to 10-15 thousand oersteds have been investigated in Moscow at the Institute of Atomic Energy of the USSR Academy of Sciences. The range of assemblies on which these researches have been made so far has been given the general title of *Tokamak*.

The main results of experimental investigations into the heating plasma by electrical discharges in doughnut chambers are as follow:

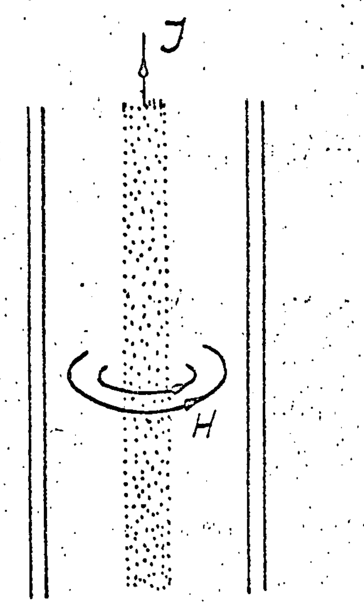

FIGURE 1.

1. In assemblies of the *Zeta* type the plasma string falls prey to instability. As a result the energy provided by the electric supply is not accumulated in the plasma but escapes to the chamber walls. So these systems cannot be considered as holding much prospect for the production of super-high temperatures. The explanation of physical processes in unstable plasma is of some interest, and is now the subject of research work being carried out on the *Alpha* assembly. From a practical viewpoint, however, the results of these investigations must be relegated to the sphere of the "pathology" of plasma.

2. In assemblies belonging to the *Tokamak* family the plasma cord, which is supported on the "corset" of the powerful longitudinal field, does not display external signs of crude instability. It therefore justifies the hope that it will be possible to achieve sufficiently effective plasma heating in such rigs. The temperature which it has so far been possible to obtain in investigation conducted with the *Tokamak* range of assemblies is still very modest, and does not exceed 100,000 to 200,000°C. However, experiments show that the plasma temperature rises as the longitudinal field is increased. We can therefore reckon that in assemblies with fields of 50 to 100,000 oersteds it will be possible to heat deuterium plasma to a temperature of several million degrees and to maintain this temperature for time intervals measured in several thousandths or even hundredths of a second—and in the time-scales which characterize the duration of events occurring in plasma these are very long periods. It is nevertheless still difficult to count on this path leading us directly to super-high, thermonuclear temperatures.

In contemporary research on thermonuclear fusion the greatest attention is being paid to the extensive class of systems for the retention of plasma which have been given the name of "magnetic traps". This term embraces various devices characterized by the one main feature that in them the function of magnetic heat insulation is wholly assigned to an external field.

Let us first examine the characteristics of the so-called magnetic-mirror traps. To understand their operating principle, let us imagine a pencil of lines of force compressed at both ends. A field of this type can be set up, for example, by using two parallel coils with current flowing in the same direction (Figure 2). Where the pencil of lines of force is compressed the field intensity is at its highest. Calculation of the movement of charged particles in magnetic fields shows that a particle travelling in the region of an increasing field experiences the action of a force which tends to deflect it in the direction of the weak field. Particles in which the longitudinal velocity is small compared with the transverse velocity will therefore be reflected from a powerful field region: hence the name magnetic mirror. In a field which increases on either side of a middle region particles must be reflected from both sides and will therefore be trapped. In principle, by accumulating sufficient trapped particles of high energy in such a magnetic system it is possible to create the conditions required for an intense thermonuclear reaction.

Many different methods have been proposed for the accumulation of fast particles in magnetic-mirror traps. Most of them are based on a scheme whereby an intense beam of fast particles is admitted into the trap, and collides with the atoms

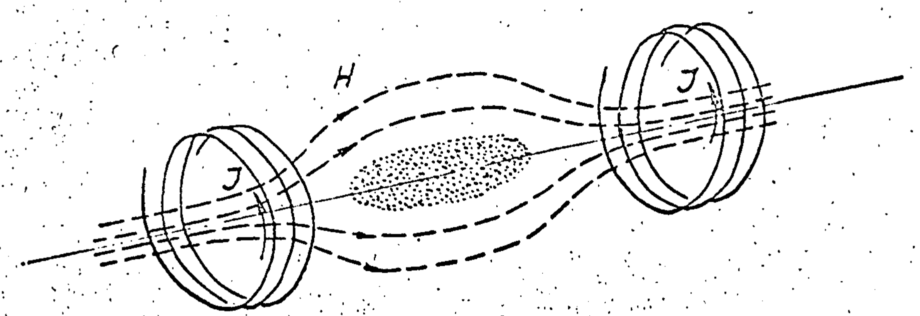

FIGURE 2.

Soviet research on controlled fusion *continued*

of the residual gas (or with previously accumulated particles) so that the incoming particles irreversibly alter their properties (charge or mass) and are therefore caught in the trap. It is also possible to accumulate particles by creating electrical discharges of various forms inside the trap.

The tempting simplicity of the design of magnetic-mirror traps has made them one of the most popular systems in today's programme of thermonuclear research. The largest magnetic-mirror trap—*Ogra*—was built in the USSR at the Institute of Atomic Energy. It is some 19 m in length and 1.4 m in diameter. In recent years research has been conducted on *Ogra* into a method of producing hot hydrogen plasma which is based on the injection of fast molecular ions of hydrogen which are broken up in collision with the residual gas, so that protons are formed and trapped. At the present time the concentration of fast protons in *Ogra* accumulated in this way is 10^7 per cubic centimetre. Further increase in concentration is hindered by instability in the particle assembly: the fast protons quickly drift away to the chamber walls.

Research is also being conducted at the Institute of Atomic Energy into another method of producing hot plasma in the mirror trap. A thin jet of cold plasma flows into the assembly chamber along the axis of the magnetic field. With the aid of a high voltage ions are drawn out of the chamber and under the influence of a radial electrical field they acquire high speeds. This system, which has been given the name of the *ionic magnetron*, enables the creation (for some tenths of a milli-second) of plasma with an ion temperature of several tens of millions of degrees at a particle concentration in the range 10^9 to 10^{10}/cm³ per cubic centimetre.

Intensive theoretical and experimental investigations into the properties of magnetic traps point unanimously to one unfortunate fact. It turns out that the plasma filling the mirror trap is subject to instability which very quickly sprays the plasma particles over the walls of the vacuum chamber. This instability is directly linked with the form of the magnetic field, which increases in the longitudinal direction on both sides of the central region of the trap, but falls, in a radial direction, in proportion to the distance from the axis. It is this radial decrease in intensity which makes it easy for the plasma to break away.

This drawback of magnetic traps has prompted interest in the investigation of magnetic systems with so-called opposing fields. A field of this form can be obtained with the aid of two coils, the current through which flows in opposite directions (Figure 3). In this sort of trap the field intensity increases in all directions from the central region. Theoretically

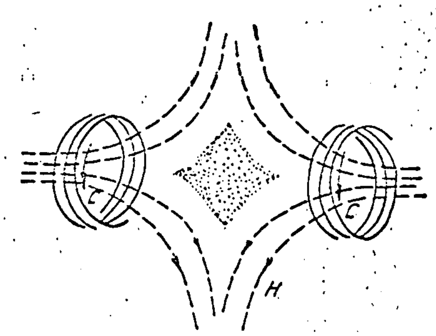

FIGURE 3.

the plasma in a trap of this kind should be free from the grosser forms of instability. However, this gain is bought at a high price. Simple physical consideration indicates that charged particles can leak out of a trap with opposing fields, coming quite close to the side edge of the area occupied by the plasma (it has the shape of a child's top).

However, the time of retention of the plasma in opposing-field traps can be determined only on an experimental basis. At the Institute of Atomic Energy a study is being made of the properties of plasma formed in the trap by the injection of a dense plasma jet from a special injector. As yet the experiments have not yielded a definite answer to the main question of the rate of escape of the particles from the trap; nevertheless the impression is that the pessimistic assessments of the theoreticians are close to the truth.

In the light of the fact that both mirror and opposing-field traps possess serious defects, thoughts naturally turn to the construction of devices with combined-type fields, in which the good points of the simple systems should be united and their shortcomings disappear. One of the simplest practical ways of realizing this idea is by superimposing a field produced by currents flowing along metal conductors arranged symmetrically in relation to the axis of the mirror system (Figure 4). The first experiments with such a combination of fields at the Institute have increased the lifetime of the plasma particles approximately by an order of magnitude. If this result can be further improved it means that there are effective methods available

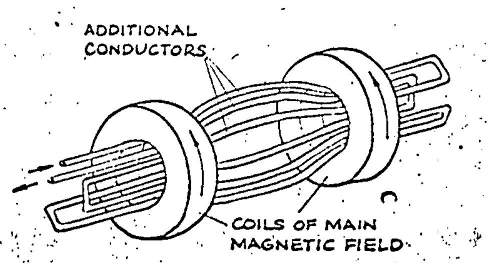

FIGURE 4.

for combating those forms of instability which today represent the main obstacle on the way towards thermonuclear temperatures..

Recently a considerable part of the programme of research into controlled fusion has been taken up by investigations into the confinement and heating of plasma by high-frequency electromagnetic fields. The future prospects for practical application of the methods of high-frequency plasma retention are somewhat obscure, and current work in this direction is in the nature of preliminary reconnaissance. In the Soviet Union this work is being conducted at the Institute of Atomic Energy and at the Sukhumi Institute of Physics of the Georgian Academy of Sciences. Research is being carried out into the behaviour of plasma in the field of a travelling electromagnetic wave, and various methods are under study for the suppression of instability using high-frequency fields. Incidentally, interesting work is also being done in Sukhumi on the processes of ultra-high-speed compression of plasma by strong magnetic fields. The heating of plasma by high-frequency fields may prove to be an extremely effective method of attaining super-high temperatures. This question is therefore receiving the unremitting attention of Soviet physicists. Research on high-frequency plasma heating is most extensively developed at the Kharkov Physico-Technical Institute of the Ukrainian Academy of Sciences. Research is also being conducted at this institute into a number of other questions of plasma physics that have direct bearing on the problem of thermonuclear fusion (in particular the question of the interaction of plasma with fluxes of fast charged particles).

In the Soviet Union work on the problem of controlled thermonuclear fusion is thus proceeding on a broad front. The work embraces a whole range of different ways of approaching the solution of the problem. Great importance is also attached to the development of a large complex of methodological and engineering investigations concerned with the diagnosis of plasma, vacuum technology of thermonuclear plants and their engineering supplies.

In conclusion it must be said that we are well aware of the vast difficulties linked with attainment of the final goal of useful power from fusion; and we are not deluded by the modest results so far achieved. Up till now the main obstacle standing in the way of controlled fusion has been the various forms of instability, with the aid of which the hot plasma easily frees itself from the shackles of magnetic heat insulation. This is really a very serious obstacle, and maximum concentration of the efforts and creative energy of physicists throughout the world is needed to enable the creation of stable high-temperature plasma

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